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Yes, You Can!

In Memory of

Leopold B. Felsen

(May 7, 1924–September 24, 2005)
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Today, addressing the technical challenges posed by system complexities requires a broad range of innovative, multidisciplinary, physics-based, problem-matched analytical and computational skills that are not adequately covered in conventional electrical-electronics (EE) engineering curricula. A great many higher educational institutions are now actively engaged in efforts to define “what makes a modern engineer” and to design curricula for teaching the necessary skills to a computer-weaned generation of students, with access to the internet and consequent globalization of information. The explosive growth of computer capabilities has revolutionized communication and the analysis of complex systems, and has made interdisciplinary exposure necessary in modern EE engineering. Physics-based modeling, observation-based parameterization, computer-based simulations, and code calibration against canonical problems (i.e., problems that have mathematical exactness and numerically computable forms) are the key issues of these challenges.

As phrased by Einstein, “in the matter of physics, first lessons should contain nothing but what is experimental and interesting to see—experimentation and hands-on training are the key issues in engineering education at least at undergraduate level.” On the other hand, with the development of new computer technologies, interactive multimedia programming languages, and the Internet, it is now possible to simulate engineering and science laboratory projects of all sorts on a computer all around the world. Experiment-oriented problems can be offered without the overhead incurred when maintaining a full laboratory. At this point the question arises: should an intelligent balance be established between real and virtual experimentations and how? Another similar problem is the balance to be maintained between teaching essentials (theory) and cranking the gear (blind computer applications). It is a general observation that the motto “I did it, it works” is widespread among the youth of today, without really grasping the general
principles and boundaries of validity of the underlying phenomena and what is even worse with a false sense of satisfaction.

Engineering, as given in the American Society for Engineering Education web site (www.asee.org), is “the art of applying scientific and mathematical principles, experience, judgment, and common sense to make things that benefit people.” That is, it is the process of producing a technical product or system to meet a specific need in a society. Engineering education is a university education, where knowledge of mathematics and natural sciences are gained, followed up by lifetime self-education where experience is piled up with practice. Therefore, the four keywords mathematics, physics, experience, and practice are the untouchables of engineering education.

Many applications in science and technology rely increasingly on field theory and circuit theory computations in either man-made or natural complex structures. Wireless communication systems, for example, pose challenging problems with respect to field propagation prediction, microwave hardware design, compatibility issues, biological hazards, and so on. Nanotechnologies, on the other hand, have challenges of locating multimillion circuit elements and subsystems on a few square centimeter chips, with very low emissions and immune to environmental interference. Moreover, need to and use of these theories are not limited to EE applications only; they are exploited in a very wide spectrum ranging from biomedical to geophysical applications. Since different problems have their own combination of geometrical features and scales, frequency ranges, material properties, and so on, no single method or approach is best suited for handling all possible cases; instead, a combination of methods, “hybridization,” is needed to attain the greatest flexibility and efficiency in engineering. Relations between field theory and network (circuit) theory play an important role in this respect.

The necessity for hybrid methods has already been recognized in the past: for example, in scattering and antenna problems, techniques have been devised that combine the method of moments (MoM) and the geometrical theory of diffraction (GTD) or physical theory of diffraction (PTD). Similarly, numerical methods such as finite elements (FE) or finite differences (FD) have been considered in conjunction with MoM, with integral equations, with boundary integrals, with modal techniques, with multipole methods, and so on. Combinations of other methods, for example, boundary contour and
mode matching or hybrid electric field integral equations (EFIE) and magnetic field integral equations (MFIE) denoted as HEM, have also been proposed.

Physics-based modeling and observable-based parameterization are very important in EE engineering education. The models that are established via well-known Maxwell equations (field theory) and transmission line equations (circuit theory) in both time and frequency domains parameterize a complex physical problem well defined that guarantees existence, uniqueness, and convergence. Field and circuit theories are dual; that is, any field problem (e.g., antenna radiation) can be transformed into a circuit theory problem and solved there (or vice versa). Starting after World War II, circuit formulations of field problems have also been employed extensively in the design of microwave, optical, and other closed and open waveguiding and radiating systems.

Another very important occurrence of hybridization is the increase in integrated circuit (IC) performance being exponential in time at rates of more than 100/decade, with the critical device dimensions shrinking and the interconnects between devices becoming smaller and more closely spaced, interconnect delays (ID) started to dominate over gate delays (GD); the ratio GD/ID of the order of 7–8 in favor of interconnects in early nineties is expected to be of the order of nearly 1/20 in favor of gates within a couple of years. As the count of active devices exceeds several tens of millions and the number of interconnects among these devices grows superlinearly with this count, efficient evaluation of time delays and signal integrity becomes more difficult and important. Devices with operating frequencies exceeding a hundred gigahertz have already appeared and today’s circuits contain millions of transistors per unit area as opposed to 1970s SPICE targeted for circuits with a few hundred transistors. Hence the need arises for a new generation of simulators with improved numerical methods using, if possible, analytic solution techniques to handle very large circuits.

Engineering as defined above is based on practice. The minima of this practice should be given during the EE education. This has become more and more comprehensive and expensive parallel to high-technology devices developed and presented to societies: computers and other microprocessor-based devices make EE engineering education not only very complex but also interdisciplinary as well. The cost of building undergraduate labs in EE may vary from 1 unit to $10^5$ units;
for example, a spectrum or a network analyzer may cost few $10^4$ units, whereas a simple software of 1 unit with or without the addition of specific cards costing $10^2$ units may turn a regular personal computer (PC) into a virtual lab. The key question therefore is to establish a balance between virtual and real labs, so as to optimize cost problems, while graduating sophisticated engineers with enough practice.

Doing numerical simulations in EE engineering has become as easy (as well as difficult) as doing measurements. It is easy because one can purchase commercial codes that do almost everything, such as supplying computer-controlled devices for measurements. The simulation packages are user friendly, have self-checking routines for control, and all can be calibrated, like most of high-tech measurement devices. On the other hand all the efforts of simulation can be in vain if one does not know how to interpret the resulting numbers. In addition, they are capable of doing only what has already been planned and included by the developer. Moreover, important concepts such as accuracy, precision, and resolution, in short the underlying theory, should be well understood by engineers.

This book aims to introduce simple, easy-to-use, but effective short codes as well as virtual tools that can be used in broad range of EE engineering lectures. The book itself may serve as a textbook for several lectures such as electromagnetic modeling and simulation, computational electromagnetics, transmission line theory, guided wave theory, diffraction theory, and others. Almost all of the virtual tools are coded in MATLAB; therefore, the reader is strongly advised to get used to working with MATLAB. The book contains 16 chapters. Roughly speaking, the first five chapters are introductory, the next five chapters are for analytical modeling, and the last six chapters are for numerical modeling and simulation.

People had to simplify problems as much as possible a century ago in order to get the feeling on the results. This is why we have had excellent canonical problems with simple analytical models. Today, we very often revisit these problems for (i) teaching electromagnetics and (ii) validation, verification, and calibration of numerical models. That is why we included many canonical problems in this book (although not very often, we also use numerical models in validation and verification of analytical models).

The first chapter is a kind of introduction which contains some fundamental modeling and simulation concepts. Validation, verification,
and calibration are briefly reviewed. Core models are given and model selection criteria are discussed. A novel electromagnetic modeling and simulation course outline, content, and flow are proposed. Then, two-level electromagnetic guided waves lecture is discussed and a highly attractive virtual tools that can be used in these lectures are reviewed. Finally, virtual tools for some advanced topics are outlined.

The second chapter presents fundamental concepts of engineering: measurement and calculation. Engineers speak with numbers therefore the true meaning of the numbers we use shall clearly be understood. Terms such as accuracy, precision, resolution, error, and uncertainty are reviewed in this chapter. Error analysis and propagation of error are given. The use of statistics in engineering, basic statistical evaluations, confidence level, and hypothesis testing (decision making) are outlined.

Some numerical analysis issues are revisited in Chapter 3. Root search of a nonlinear function, numerical integration, and differentiation, and solving systems of linear equations are reviewed and simple MATLAB scripts are introduced. Taylor’s expansion of a function is also discussed.

Chapter 4 is reserved for Fourier transformation and Fourier series representation of a function. Fourier transform has been widely used in circuit analysis and synthesis, from filter design to signal processing, image reconstruction, and so on. Fourier transform is also used in electromagnetics from antenna analysis to imaging and nondestructive measurements, even in propagation problems. In order to numerically compute the Fourier transform on a computer, discretization and numerical integration are required. This is an approximation of the mathematically defined Fourier transform in a synthetic (digital) environment; therefore, the reader should be aware of the problems related to this approximation. The true meaning of the Fourier transform and Fourier series representations, their mathematical definitions, and computer implementations are discussed in detail. Effects of discretization and finite nature of discrete Fourier transformation (DFT) and fast Fourier transformation (FFT) are shown with several examples prepared with simple MATLAB scripts.

Randomness in electromagnetics is briefly discussed in Chapter 5 together with some statistical discussions. Stochastic modeling of communication and/or radar signals is outlined. Computer generation of useful signal, noise, clutter, and interference is presented.
Chapter 6 is reserved for some basic electromagnetic terms, concept, identities, and definitions. Coordinate systems mostly used in electromagnetic, point/line source concepts, transverse electric and magnetic models in guided wave representations, and electromagnetic plane waves–transmission line analogy are presented.

Sturm–Liouville equation represents both eigenvalue (source-free) and Green’s function (source-driven) electromagnetic problems. This is briefly discussed in Chapter 7. 1D eigenvalue and Green’s function representations for both finite and infinite regions are given. The connection between these two problems established via the completeness and orthonormality relations is outlined.

A canonical two-dimensional (2D) wave propagation problem is discussed in Chapter 8. Many natural or man-made guiding environments are characterized by physical parameters that render the wave equation nonseparable in any of the standard coordinate systems. Propagation inside 2D parallel perfectly electrical conductor (PEC) plates is used to review ray optical and modal solutions which represent source-driven and source-free wave problems. The 2D Helmholtz wave equation is reviewed. 1D and 2D spectral representations in terms of a Green’s function problem and eigenfunction (normal mode) summation are summarized accordingly. The classical ray–mode interchange approach and their hybridization to home in best features of both rays and modes are also discussed. The MATLAB-based virtual tools RAYMODE and HYBRID included in this chapter can be used to visualize individual contributions of rays and modes which are very important for the reader in order to get a physical insight to this problem.

In the absence of transverse–longitudinal separability, it is not possible to define discrete or continuous normal modes that individually satisfy the transverse boundary conditions and propagate longitudinally without coupling to other modes. When transverse–longitudinal separability is only weakly perturbed, one may define local (adiabatic) modes which adapt smoothly, without intermode coupling, to the slowly changing conditions. Adiabatic modes fail in cutoff regions and can be uniformized there by intrinsic modes, which are synthesized by a spectral continuum of adiabatic modes. These concepts can be elucidated and validated by investigating the wave dynamics in a simple test environment: A wedge waveguide with nonpenetrable boundaries. This canonical problem is discussed in Chapter 9.
High frequency asymptotics (HFA) are presented in Chapter 10. HFA approaches have long been used in electromagnetics. HFA methods include geometrical optics (GO), geometrical theory of diffraction (GTD), its uniform extension uniform theory of diffraction (UTD), physical optics (PO), physical theory of diffraction (PTD), elementary edge waves (EEWs), and parabolic equation (PE) methods. The GO, GTD, and UTD are ray-based diffraction methods; PO and PTD are induced-source-based methods. HFA techniques are reviewed through a classical, canonical problem: EM wave scattering from a wedge shaped object with PEC boundaries. A MATLAB-based virtual diffraction tool WedgeGUI, using analytical exact as well as HFA techniques, is also introduced. Both line source and plane wave illuminations are analyzed. Effects of various parameters on the reflection, refraction, and diffraction are investigated. Comparisons among GO, GTD/UTD, PO/PTD, and PE models through many scenarios are presented.

Chapter 11 deals with antenna arrays. Arrays of isotropic radiators are taken into account and boresight/end-fire beam forming, beam steering are discussed on linear, circular, and planar arrays of isotropic radiators. A simple MATLAB-based virtual tool ARRAY is prepared and introduced for the students and lecturers who think that 2D and 3D visualizations of array patterns could be very effective in learning/teaching antenna arrays. The ground effects on the vertical radiation patterns are also investigated via a simple MATLAB script.

Chapter 12 presents another interesting MATLAB virtual tool which explores guided wave propagation modeling using the Snell law. Electromagnetic guiding occurs along regions which are physically bounded transversely and/or where waves are confined due to the medium parameter variations. For example, ground waves propagate through surface and/or elevated ducts formed by the refractivity variations of the atmosphere. The MATLAB-based ray shooting virtual tool SNELL may be used to explore transverse ray confinement due to linear, bilinear, and trilinear refractivity variations. It is amazing to see how a simple equation—Snell law—can numerically be used to visualize all the ray behaviors under different refractivity conditions. The formation of various surface and or elevated ducts may be observed only by changing the refractivity profiles.

Chapter 13 introduces method of moments (MoM): one of the earliest numerical models. The model is based on segmentation of the...
object/environment under investigation. Surface currents caused by any specified electromagnetic source are obtained by using Green’s function solution of the problem. Then, the scattered field caused by each segment is calculated and total scattered field is obtained by the application of the superposition principle over all segments. The method is first explained through a simple electrostatic application: parallel plate capacitor modeling. Then, propagation over nonpenetrable flat earth is discussed and MoM results are compared with analytical reference data. Scattering from infinitely long PEC cylinders with arbitrary cross section is also modeled with MoM. MoM modeling of a few complex radiation and scattering problems are also discussed. Finally, wedge diffraction and propagation inside a wedge waveguide are modeled using MoM.

Chapter 14 presents finite-difference time-domain (FDTD) method. FDTD method is first used to represent plane waves and discretization effects, stability, numerical dispersion, source-injection, boundary implementation are all reviewed. Then, 1D FDTD is used to model transmission lines. Starting with the fundamental TL theory, basic concepts such as characteristic impedance, voltage and current reflections under different terminations, and standing wave formation are reviewed. The generic time-domain TL equations are discussed using the analogy between plane waves and transmission lines. An effective MATLAB-based virtual tool TDRMETER is introduced to numerically test time-domain reflectometers. Time-domain reflectometers have long been used in EE engineering; initially by the power and telephone engineers to find out SC or OC problems along hundreds of kilometers long transmission lines without doing physical search. Fault location and identification using Fourier and Laplace transformations are also included. The FDTD problem is also discussed through second-order decoupled 1D wave equations. Then, 2D FDTD modeling is discussed through three different virtual tools. First, MGL-2D is presented where broad range of 2D scenarios can be created by the user and electromagnetic waves can be visualized. It includes modeling of TE and TM problems. Any penetrable and/or nonpenetrable rectangular, circular, or triangular material can easily be located inside the 2D computation space and electromagnetic scattering effects can be visualized. Perfectly reflecting or absorbing termination can be specified at the four edges of the space. Both narrowband and broadband (pulsed) wave propagation can be taken into account. Finally, the WedgeFDTD virtual tool is
given for the observation of wedge-diffracted waves and FDTD versus HFA comparisons.

Chapter 15 presents parabolic equation (PE) modeling. The PE model has long been used in propagation modeling and can handle boundary irregularities as well as medium variations. Both split-step parabolic equation (SSPE) and finite-element method (FEM) implementation are introduced. Simple MATLAB scripts for SSPE and FEMPE solutions of both narrow- and wide-angle models are given. These models are validated against analytical model for a 2D surface duct problem where ducting is controlled by a vertically decreasing linear refractivity profile. This problem has an analytical exact mode summation solution in terms of Airy functions. Then, a 2D groundwave propagator GrSSPE is presented. GrSSPE developed in a way to let the user draw his/her own longitudinal terrain profile by just clicking the computer mouse and supply various input parameters. The rest is done automatically by the virtual tool. The output is a 3D color plot representing field strength versus range/height. The formation of various surface and or elevated ducts may be observed by changing the parameters and terrain profiles. Chapter 14 also discusses analytical and numerical modeling of the 2D dielectric slab waveguide (i.e., optical film). The exact wave solutions can be derived from the 2D wave equation in terms of mode summation. Mathematical representations of the modes can be extracted directly or through a simplification of even- and odd-symmetry applications. An interesting MATLAB-based virtual tool DiSLAB is developed which compares mathematical solutions against the split-step parabolic equation results. The reader may also enjoy extraction of eigenvalues from propagation characteristics inside the slab waveguide by using the longitudinal correlation function and its Fourier transform.

Chapter 16 revisits the 2D parallel plate nonpenetrable waveguide and analytical and numerical models are compared. Tables of stand alone codes for mode summation, ray summation, image method, SSPE, MoM, and FDTD are given.

Appendix A presents introductory material for MATLAB use. Appendix B lists some useful books for both electromagnetics and computational electromagnetics. Most of these books have become classical, e.g., the book by Felsen and Marcuvitz, by Don Dudley, R. E. Collin, J. D. Kraus, R. F. Harrington, and by W. L. Stutzman, G. A. Thiele should be among the books the reader have in their library.
Finally, Appendix C lists tutorials for both fundamental issues and electromagnetic virtual tools that are discussed in this book. The reader is referred to these papers for the complete references of each virtual tool.

All the virtual tools are gathered and uploaded in the publisher’s website. Sample scenarios and canonical comparisons are included. Moreover, some nice video clips recorded during characteristic simulations are also presented.

Note that MATLAB scripts are mostly prepared with the classical coding approach in order to make them compact and easily traceable. On the other hand, MATLAB-based virtual tools use all advanced level coding approaches and commands. Note also that this book primarily is neither about fundamental EM theory nor about numerical models included (FDTD, MoM, and SSPE). There are excellent books which has become classic and are listed in Appendix B. This book is primarily about EM modeling and simulation with the emphasis on the modeling and simulation side. It is a “how to” or “let’s do it!” type book. It touches upon wide range of problems and discusses several canonical scenarios. Because of these, some of the chapters, on purpose, are reviewed briefly with one or two short MATLAB scripts, while others are discussed in detail using several scripts as well as virtual tools. Each chapter is pretty much stand alone.

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About the Author

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Born in Akhisar, Turkey, in 1958, Dr. Sevgi graduated from the Electronics and Communications Engineering Department of Istanbul Technical University (ITU) and completed his PhD studies with Professor Leopold B. Felsen at the Weber Research Institute/Polytechnic University in New York.


He has been involved with complex electromagnetic problems and systems for more than two decades. His research study has focused on analytical and numerical methods in electromagnetics, high frequency asymptotic (HFA) approaches, FDTD, TLM, FEM, SSPE, and MoM techniques and their applications, propagation in complex environments, diffraction modeling, microwave circuit design, EMC/EMI modeling and measurement, sensors and integrated surveillance systems, surface wave HF radars, RCS modeling, and bioelectromagnetics. He is also interested in novel approaches in engineering.
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He is a fellow of the IEEE, associate editor of the IEEE Antennas and Propagation magazine, the writer/editor of the “Testing Ourselves” Column, and member of the IEEE Antennas and Propagation Society AdCom (2013–2015) and Education Committee.